Feed-forward vibration compensation for small telescopes

Andreas Sinn, Stephan Schachner, Thomas Riel, Christian Schwaer, and Georg Schitter

Automation and Control Institute (ACIN), TU Wien, Gusshausstrasse 27-29, 1040 Vienna, Austria

ABSTRACT

This publication investigates the applicability of feed-forward vibration compensation for small telescope systems in one axis, based on commercial-off-the-shelf accelerometers and a fast-steering mirror (FSM). The vibrations are measured with multiple accelerometers and their influence onto the optical path is reconstructed using a high-pass filtered double integrator. Consequently, the reconstructed deviations are compensated in a feed-forward control manner by the FSM. A quad-photo-diode and an artificial star are used for verification of the performance of the system. Exemplary disturbance spectra are acquired on a roof-top using a small telescope system. They are applied to the developed system in a laboratory environment, successfully demonstrating the applicability of the proposed compensation concept by reducing the RMS tip-tilt error of the azimuth axis by a factor of 2.2 in the relevant frequency range.

Keywords: Vibration compensation, small telescope system, feed-forward control, tip-tilt compensation

1. INTRODUCTION

Small telescope systems are used for a variety of applications ranging from classical astronomy[1] over optical satellite communication[2] to space debris observation.[3] One limiting factor of their imaging quality is the influence of vibrations caused by wind shake, ground vibrations and undesired movements of the telescope mount. These vibrations mainly cause low order aberrations, especially tip-tilt errors.[4] Even though the influence of vibrations in general decreases with decreasing telescope size,[5] especially wind gusts may have a considerable impact on the telescope system.[6] Typical disturbance spectra range up to 80 Hz[4,7,8] and also resonances of the mechanical system (mount, telescope tube) are typically located in this range.[9] Both may exceed the control bandwidth of state of the art telescope mounts[10] significantly and therefore, reduce the performance of the telescope.

Typical compensation approaches, such as adaptive optics used successfully in larger telescopes, require some sort of wavefront sensor to implement feedback control and thus, claim a significant portion of the collected light.[11,12] However, even with an active feedback control loop the achievable disturbance rejection is limited and especially sharp system resonances may not be suppressed sufficiently.

Feed-forward disturbance compensation based on inertial metrology, e.g. accelerometers, has the potential to overcome these limitations and reduce the impact of vibrations on small telescope systems without requiring light from the application. It is successfully in use in large telescope systems[5,7,13–15] as well as other applications.[16,17] Both sensor placement[18] as well as type and resulting quality of the reconstruction approach[5] are essential to achieve good vibration compensation performance. However, the applicability and the potential improvement using a feed-forward compensation system has not been investigated in detail for small telescope systems.

The contribution of this publication is the successful demonstration of feed-forward vibration compensation in a small telescope system using inertial metrology. A fast-steering mirror (FSM) is used to correct disturbances measured by an accelerometer, which are reconstructed to angular position deviations. Outdoor disturbance spectra in presence of wind are recorded on a roof-top and used for validation of the chosen approach.

Further author information: (Send correspondence to Andreas Sinn)
Andreas Sinn.: E-mail: sinn@acin.tuwien.ac.at, Telephone:+43 1 58801 376525

Published version of the article: Andreas Sinn, Stephan Schachner, Thomas Riel, Christian Schwaer, and Georg Schitter, "Feed-forward vibration compensation for small telescopes," *Proc. SPIE 12188, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V* 121883H , 2022. DOI: 10.1117/12.2626965

2. SYSTEM DESCRIPTION

The proposed system is based on a 25-cm Schmidt-Cassegrain telescope (LX200 GPS, Meade Instruments, USA) with a DDM60 mount (ASA Astrosysteme, Austria) in alt-az configuration mounted on a mobile workbench. The wheels of the workbench are retractable, ensuring a stable connection to the ground during measurements. The block diagram of the proposed compensation approach is shown in Figure 1.

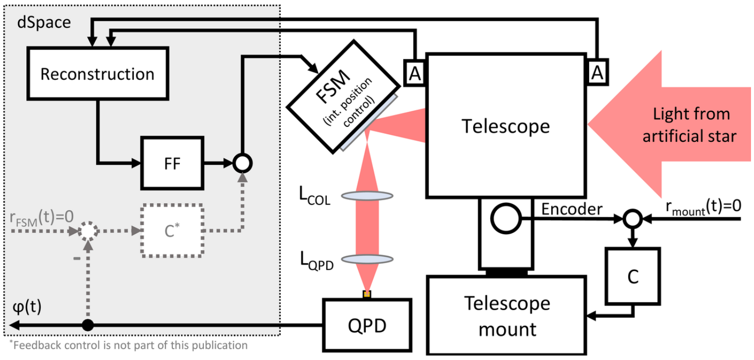

Figure 1. Block diagram of the proposed feed-forward compensation system.

Two low-noise MEMS accelerometers (ADXL354, Analog Devices, USA) with analog outputs are attached to the telescope: One at the secondary mirror mount (Figure 2(b)) and the other one at the back of the primary mirror cell (Figure 2(c)). They provide a measurement bandwidth of 1.9 kHz, which is sufficient to prevent phase lag in the frequency region of interest (< 100 Hz). Instrumentation amplifiers (INA111P, Texas Instruments, USA) are used to amplify the output signals which then are recorded by a rapid prototyping system (MicroLabBox, dSpace GmbH, Paderborn, Germany) running at 20 kHz. This system is also used for the digital implementation of the reconstruction algorithm and feed-forward control (Section 3). A 1-inch voice-coil actuated FSM (OIM101, Optics in Motion LLC, California, USA) is installed instead of a standard zenith-mirror. The FSM has an integrated analog position controller operating with a closed-loop bandwidth of 530 Hz (Figure 5). The analog setpoints for the FSM are supplied by the dSpace system. The setpoints $r_{mount}(t)$ for the internal position controllers of the telescope mount are kept constant to point the telescope at a artificial star.

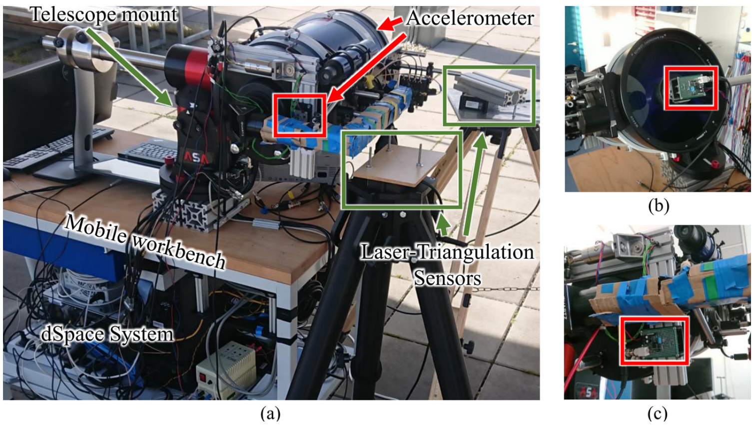

Figure 2. Implemented setup of the proposed compensation approach on a mobile workbench. (a) Image of the full system and two laser triangulation sensors on individual tripods for verification of the position reconstruction. (b) Accelerometer attached to the secondary mirror mount. (c) Accelerometer attached to the back of the primary mirror cell.

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An artificial star consisting of a red LED with a pinhole is used as optical reference source for the measurements in this publication. The incident light is collimated after the FSM by the lens L_{COL} and relayed to an optical breadboard attached to the side of the telescope. The lens L_{QPD} focuses the beam onto a custom-made quad-photo-diode (QPD, based on S5980, Hamamatsu, Japan). The outputs of the QPD are recorded by the dSpace system and transformed into the angular deviation $\varphi(t)$ (details in Section 3), which is used as a reference measurement. The dotted blocks indicating a feedback-control loop are shown to compare the proposed system to an approach using QPD sensor feedback.[12] In case of an already existing feedback loop for the FSM the proposed feed-forward compensation may be used in addition. In this case the internal position controller of the FSM could be omitted, increasing the achievable closed-loop bandwidth.

Figure 2(a) shows an image of the full system on a roof-top. Additionally, two laser triangulation sensors (ILD2240, Micro-Epsilon Measurement Technology, Ortenburg, Germany) are set up on independent tripods and are used to verify the reconstructed positions from the accelerometers.

3. POSE RECONSTRUCTION AND FEED-FORWARD CONTROL

For the proposed feed-forward compensation approach a two step process is required. First, a reconstruction of the position, in this case angular deviations (tip-tilt) from the measured accelerations is required. Second, a feed-forward control filter needs to be designed. An universal option for position reconstruction is double integration of the acceleration signal.[5] To stabilize this open double integrator at low frequencies a fourth order high-pass filter[19] is added. The resulting transfer function of the reconstruction filter G(s) is given by

$$G(s) = \frac{s^2}{(s^2 + 2\zeta w_c s + w_c^2)^2}, \tag{1}$$

where s is the Laplace variable, w_c the cutoff frequency of the high-pass filter and ζ the damping coefficient. This approach provides a solution, which does not require in-depth knowledge of the system and especially disturbance spectra, except for selection of the cutoff frequency.[13] Figure 3 depicts the Bode plot of a double integrator and $G(s)$ implemented with a cutoff frequency of 1 Hz. Purely integrating behavior is visible above 5 Hz. As intended the magnitude drops for frequencies below 1 Hz. However, the high-pass filter also affects the phase, resulting in a 90° phase shift at 1 Hz and increases further towards lower frequencies.[5] As disturbances below 1 Hz are typically covered by the telescope mount,[10] this increasing phase shift does not affect the performance of the telescope system.

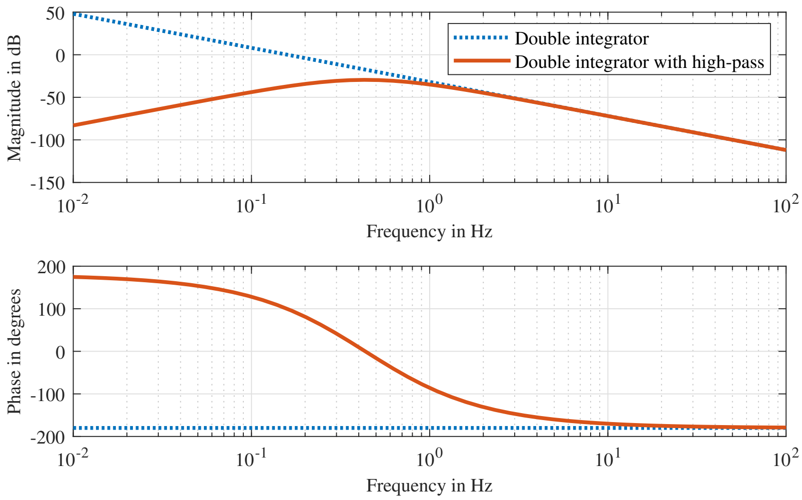

Figure 3. Frequency response comparison of a double integrator (dotted blue) and a double integrator with a 4^{th} order high-pass filter (solid orange) used for reconstruction of the position.

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The angular deviation $\varphi(t)$ is calculated from the two reconstructed, translational position deviations and the geometric properties of the telescope. The measured acceleration time signal of one sensor and the corresponding reconstructed translational position are shown in Figure 4. The displayed acceleration signal (top) is median filtered, to make the relevant, low frequency components clearly visible. In the reconstruction process no median filter is applied, as high frequency components and noise are suppressed by the double integrator. The reconstructed position (bottom) is compared to an external position measurement acquired by the triangulation sensor. The two signals show acceptable agreement in terms of amplitude and phase. However, some high-frequent components in the triangulation sensor signal are not visible in the reconstructed position, but are not considered to be an issue for this feasibility analysis. Potential accelerations caused by the telescope mount during tracking of an object are low-frequent with small amplitudes and therefore, do not show up in the reconstructed position.

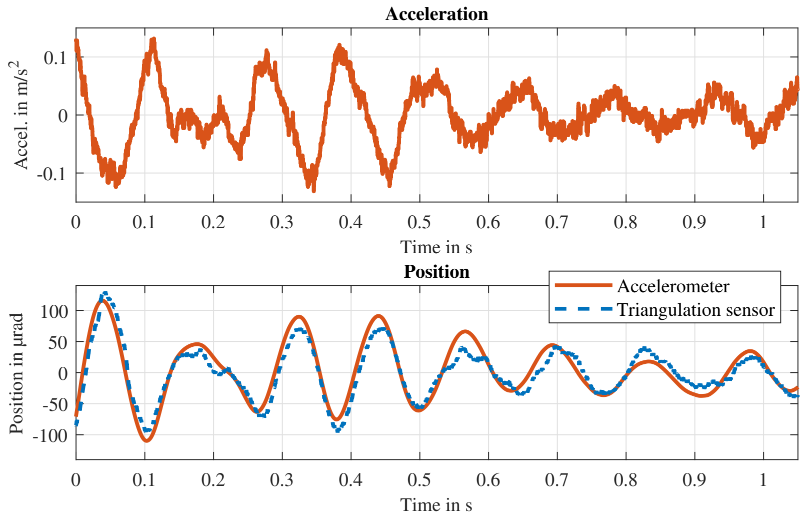

Figure 4. Measured acceleration time signal (top) of the azimuth axis acquired on a roof-top in presence of up to 8 m/s winds. The bottom plot shows the reconstructed position (solid orange) in comparison to an external position measurement (dashed blue).

The reconstructed position needs to be mapped onto the FSM to complete the feed-forward compensation system. Typically this step is done by applying the inverse plant dynamics and an additional low-pass filter to the position.[20] In this publication the position of the FSM is internally feedback controlled. The corresponding frequency response of the FSM is shown in Figure 5, indicating good reference tracking in the relevant frequency range with a small phase lag of 16° at 100 Hz. Therefore, the inverted plant is essentially reduced to an inverter with a static gain, which maps the angular deviation of the telescope to the FSM-space. Low-pass behavior is provided by the double integrator and the dynamics of the FSM. The output of the feed-forward compensation block is then applied directly as setpoint for the integrated position controller of the FSM. As the double integrator is stabilized by a high-pass filter, no position drift is introduced by the proposed system.

4. MEASUREMENT RESULTS AND DISCUSSION

To enable a fair comparison of the proposed system with and without feed-forward compensation, a typical azimuth angular disturbance spectrum is recorded as reference on a roof-top of a 6-story building in urban environment in presence of wind with an average velocity of 8 m/s. Afterwards this spectrum is applied to the reference input $\mathrm{r}_{mount}(\mathrm{t})$ of the telescope mount in a laboratory environment introducing comparable and reproducible disturbances to the system. The QPD is used as reference sensor to measure the angular deviations while the telescope points towards an artificial star.

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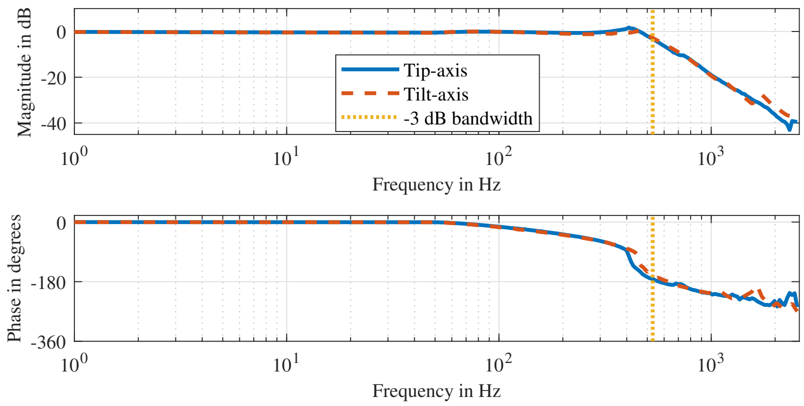

Figure 5. Bode plot of both axes of the used FSM. It is equipped with integrated position feedback controllers and tuned for a -3 dB bandwidth of 530 Hz.

In a first step, the disturbance is applied without compensation resulting in the dashed blue line of Figure 6, showing the RMS error of φ over the relevant frequency range. In this case the reference input of the FSM is set to zero. One dominant resonance of the system (mobile workbench) at 11 Hz is excited by the disturbance and clearly visible in the spectrum besides others at 3.7 Hz and 24 Hz.

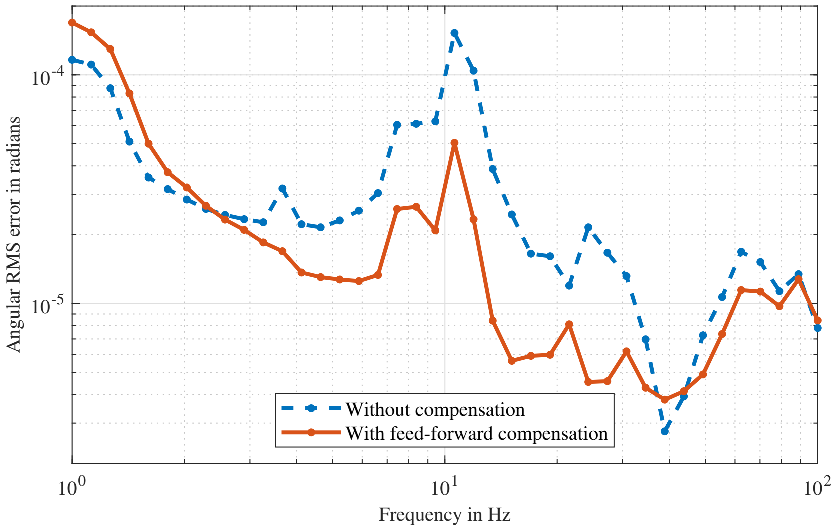

Figure 6. Frequency domain representation of the measured angular deviation without (dashed blue) and with (solid orange) the proposed feed-forward compensation. Between 2.6 Hz and 40 Hz a clear reduction of the error is visible.

In a second step, the proposed feed-forward compensation system is activated and the same disturbance spectrum is applied. The resulting frequency behavior (solid orange line in Figure 6) demonstrates a significant reduction of the angular RMS error in the frequency range between 2.6 Hz to 90 Hz. Below 2.3 Hz the system increases the angular error slightly, due to the increasing phase shift of the high-pass filtered double integrator towards lower frequencies (90° at 1 Hz). A reduction by a factor 2.2 over the full observed frequency range is visible with a maximum error reduction of 4.74, resulting in a RMS error of 47 µrad.

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The presented measurement results demonstrate the feasibility and potential of accelerometer-based feed-forward vibration compensation for small telescope systems, resulting in a 2-fold reduction of the RMS error without requiring light from the telescope.

5. CONCLUSION

This paper introduces feed-forward vibration compensation for one axis of a small telescope by means of measuring accelerations and compensating them with a fast steering mirror (FSM). The position deviations are reconstructed from the measured accelerations using a high-pass filtered double integrator, propagated through a feed-forward filter and applied to the FSM. Representative disturbance spectra for a 25-cm telescope system are recorded on a roof-top in presence of wind velocities of 8 m/s and used as artificial disturbance for evaluation of the compensation setup in a laboratory environment. Using the proposed system the azimuth angular RMS error is reduced by a factor of 2.2 down to 47 µrad covering the relevant frequency range from 1 to 100 Hz, successfully demonstrating the feasibility of the chosen approach, enabling a better performance of the telescope system while providing 100% of the light for the application.

Future work concerns the combination of the proposed feed-forward approach with a feedback controlled tip-tilt compensation system based on a measurement with a quad-photo-diode.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the excellent cooperation with ASA Astrosysteme GmbH and thank for their support and fruitful discussions.

This work has been by the Austrian Ministry for Transport, Innovation and Technology (BMVIT) under the scope of the Austrian Space Applications Program (FFG project number 854050) and is funded by the Austrian defense research programme FORTE of the Federal Ministry of Agriculture, Regions and Tourism (BMLRT).

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